# A Low-Carbon Concrete Building Code

*Towards a carbon-sequestering built environment*

*Policymakers around the world are recognizing that climate change policies for the construction sector that focus entirely on operating carbon are only a partial solution . . . the groundwork is in place for consideration of embodied carbon. ([1])*

*A city's built environment today can contain over 300 tons of building materials per capita, more than triple the material intensity compared to 1960. The environmental impact of adding all of this material – building and infrastructure construction, including the full supply chain related to building materials – accounts for up to 20% of global greenhouse gas emissions. [[2]]*

## Summary

Good news and bad news. First, the bad: six to eight percent of global greenhouse gas emissions come from the production of a single product: portland cement, the "glue" that binds sand and gravel into the many forms of artificial rock we call concrete. The construction industry has been habituated for decades to using much more cement in concrete than necessary, even in this time of accelerating climate disruption, yet no building code, green standard or public policy does more than weakly suggest a reduction of cement usage. We haven't addressed the considerable *embodied* emissions in cement or other building materials.

Now the good news: the technologies and industry culture for low-carbon concrete are finally emerging, largely in anticipation of an effective price on carbon. We know how to make very high quality concrete with radically reduced emissions—somewhat like the ancient Romans did—but don't have the impetus that will shift a very conservative industry. What's needed now is a catalytic amendment to code provisions that will compel more climate–friendly concrete, and effectively put a price on embodied emissions. That effort can probably only originate at the local level, where the weighty influence of entrenched industry cannot so easily sabotage reform.

Bay Area counties are uniquely poised to make that effort, for here we have a culture of engineers, builders, and even concrete suppliers who are *already* using low-carbon concrete, and have been for some years. We have proven the technology, and now need to write and enact a low-carbon building code in a way that is practical, verifiable, and most importantly adaptable by other jurisdictions around North America.

And that's just a beginning. A successful enactment of a low-carbon concrete building code in Bay Area counties can and must serve as a template to expand *geographically* as far as China and India, where the vast bulk of concrete will be placed in the next few decades, as well as *materially* so as to include other carbon-intense building components like metals and refrigerants.

The Bay Area Air Quality Management District (BAAQMD) is providing funding to launch just such an effort. Led by Marin and Alameda Counties, the effort will develop with an *ad hoc* collaboration of Ecological Building Network, StopWaste, Arup, Central Concrete, and other interested stakeholders. The project will provide County supervisors with adoptable provisions at the end of 2019 for inclusion with the usual triennial code update, as well as model specifications and case studies.

## 1. Problem and Opportunity *What is "embodied carbon" and why care?*

Current green building standards such as LEED and CALGreen focus primarily on reducing the *operating* energy (and consequent emissions) of buildings, such as the power required to heat, cool, and light homes and businesses. These efforts are necessary, for in the life of a building that is where most emissions occur. As California moves closer to Zero Net Energy homes, however, the share of emissions from operational energy drops substantially, making the largest source of a building's climate *impact* it's *embodied* emissions (Figure 1). Embodied emissions are those generated by making and transporting the materials to the building site, including mining, refining, and shipping.

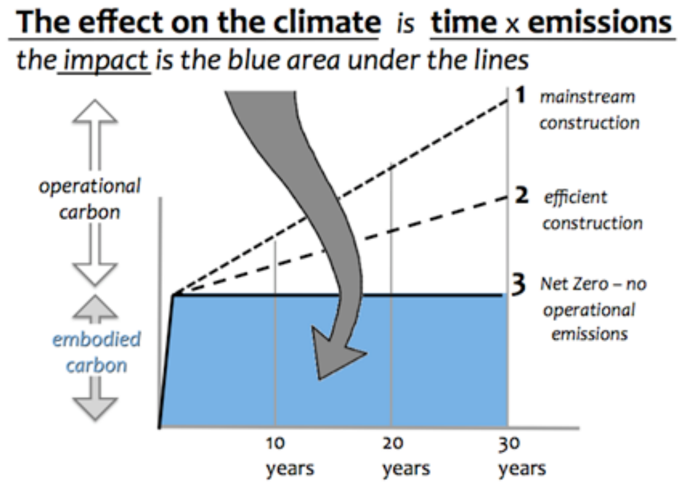



Figure 1. Embodied vs. operational emissions.
Source: *"The New Carbon Architecture"*

A construction project's embodied emissions enter the air right at the start, frontloading the project's climate impact with no way to mitigate those impacts later on. The importance of emissions released into the air now, rather than attenuated over decades to come, is referred to as the *time value of carbon*, which highlights the pressing need to reduce emissions globally in the near term more than the long.

There is a very large silver lining to this particular cloud. Attention to embodied carbon has revealed an exciting possibility: a carbon-positive architecture. Building with carbon-rich materials such as wood, hemp, straw, and captured carbon emissions, in the rapidly growing number of ways that we can, holds the possibility of transforming the built environment into a massive carbon *sink*. Even concrete might some day be a (net) carbon-absorbing material, but for the nearer term of this project, focus will be on moving its footprint towards zero.

## 2. Building Codes and Climate *moving from myopic to global*

> *The Paris Agreement goal of keeping global warming to well below 2°C . . . will require carbon-neutral or carbon-negative construction everywhere from 2030 onwards, which implies the need to rapidly scale up the use of building materials with zero or negative emissions in the next decade. . . . technological innovation and diffusion will take too long under a business-as-usual scenario. Given the urgency of the challenge and the time taken historically for technology systems to evolve, a considerable push will be needed to get the next generation of low-carbon cements out of the lab and into the market. . . . In the coming years, large quantities of concrete will continue to be used, and transforming how it is made to radically reduce the use of Portland cement is essential.* [3]

In the 90 years since adoption of the first modern building codes, they have grown from the size of a small paperback novel to the size of a modest urban library, having absorbed by reference our vastly growing body of technical knowledge about building. They do impose costs and delays, as every permit applicant in the industrialized world bemoans, but they have also done a stunningly successful job at protecting us from obvious risks like fire, earthquake, poor water supply, sanitation or ventilation, and other risks to human health.

But their concern has always ended almost entirely at the property line; what happens in the broader world is someone else's concern. That has seemed a reasonable boundary until recently, but in this time of growing population and accelerating climate disruption we are all much more connected, and well-being (or its opposite) doesn't happen in isolation. This obliges us to rethink building regulation to address the considerable greenhouse gas emissions from the built environment. The possibility before us is not just to do less bad, but to do ecologically good things and move towards regenerative buildings and cities that act like forests to clean the air and water, and absorb atmospheric carbon.

That's the lofty overarching concept, but where should we start? The starting place is obvious and wildly unsexy: the most common product in the world, concrete.

## 3. the Reinvention of Concrete

*Concrete* is artificial rock: you mix up some sand and gravel with some kind of glue, and then pour it or spray it or pack it into whatever form you want to get the desired shape when it hardens. That's how you make a concrete block, an adobe brick, a sheet of gypsum board, a city sidewalk, Hoover Dam, an interstate highway, or the Pantheon—to name just a few among thousands of examples. That's how you build most of the buildings that human beings have ever built—with sand and gravel glued together. There might also be some fibers or chemical additives or other interesting ingredients, and it gets much, much more complicated than you might think, but that's the gist of it: gravel and glue.

"Concrete" as most people think of it is sand and gravel glued together with *portland cement*, which is basically made by heating and grinding limestone. When it was invented in England 200 years ago, portland cement was a technological leap forward from the lime plasters that had been around in many forms all over the world for millenia. The inventor Joseph Aspdin found by trial and error that by burning the limestone hotter (over 2500 °F) and intermixing ground clay he could get a vastly better product. It set up faster, was stronger quicker, could be used underwater, and in many ways was just better than anything we'd had before. And so it took over, and is now the most commonly used building material in the world after water, sand and gravel. It was a truly great and game-changing technology, now embedded into our standards and codes and therefore intimately part of almost all building projects. So why do we need reinvention? What's the matter with that?

Two very large problems with that. One, you put a ton or more of carbon in the air for every ton of portland cement produced; at that rate cement production today accounts for six to eight percent of all anthropogenic global emissions. Two, there's not enough: there's not enough global cement-making capacity to take care of the next two billion people due in the next twenty or so years. Even with all the Portland cement and other cementitious materials in the world, we won't be able to place as much concrete—by current methods—as will be needed to house, educate and shelter everybody. For the climate and for our children, we need to reinvent concrete.

Recognizing the need to reimagine concrete and improve its quality, the American Concrete Institute has dropped its requirement for minimum cement contents in concrete, as written into their standard ACI 318, which serves as the basis for most modern North American building codes. As stated in their commentary([4]):

> *There is no requirement for minimum cement or cementitious materials content in ACI 318. . . . Historically, when concrete was proportioned with only portland cement, a minimum cement content was commonly specified to ensure that the strength and durability requirements were met. As concrete technology and industry expertise have evolved, there is a better understanding of factors affecting performance of concrete, thereby rendering minimum cement content requirements obsolete . . . There is no technical basis for specifying cement content if the performance requirements are defined.*

I have been a practicing structural engineer for 40 years, with experience (for example) on San Francisco highrise, Miami hospitals, Denver office parks, and residential structures of every type all over the world. In all of that, every engineer I ever learned from drilled into me the need to require minimum—and typically excessive—cement content in concrete mixes. That was widely accepted in my profession as cheap insurance against expensive problems with inadequate strength. All for good reason: no one wants to learn that the foundation concrete is inadequate after having erected five stories of steel framing. Further, the use of supplementary cementitious materials (SCMs) such as fly ash and slag were treated askance, "like soybeans in the hamburger" as one witty colleague put it.

Now, some decades later, we've learned much more, and ACI has published extensive standards and commentary about the many beneficial effects of using SCMs (even aside from climate considerations), as well as the deleterious effects of excessive cement content. So our understanding and standards have evolved, but the industry itself is very slow to change; many engineers and readymix suppliers are strongly habituated to stipulating cement contents that, as some now say, belong in a museum.

You can make concrete—artificial rock—with all sorts of "glues" besides portland cement, and we do so all the time; other concretes meet other needs. *Asphaltic* concrete serves very well as durable but slightly flexible paving for most streets and highways. *Gypsum* concrete makes great fire-resistive wallboard. The many forms of *clay* concrete used by our ancestors, or *earthen construction* as we now call it, very much live on today in both traditional and modernized versions of adobe bricks, rammed earth, cob, and wall plasters. Though not generally as strong or durable as portland cement concrete, clay concrete of one form or another meets needs of many building projects at a vastly lower climate cost. Finally, in what we take to be just the beginning of a biomimetic building industry, companies like BioMASON are making bricks with enzymes by mimicking the works of tropical termites.

Of more large scale promise for larger building structures, for now, are the various cement supplements and alternatives as are being actively explored (see Table 1). Feedstock for these SCMs and Alternative Cements (AC) include various industrial waste products, certain natural volcanic soils (like the Romans used), magnesium and other oxides, and, most widespread of all, clay. The availability of any of these materials varies greatly both with market conditions (e.g., as coal-fired power fades in the USA, supplies of *fly ash*, the dust collected at the smokestack and an excellent SCM, decrease in tandem), and with geography (using the same example, there's lots of fly ash in the central and eastern USA, but no coal-fired power plants closer than a thousand miles from San Francisco.

## Low-carbon cements at different stages of the innovation cycle

| Phase | Technology | Examples |
|---|---|---|
| Research phase | Magnesium-based cements | Novacem |
| Pilot phase | Cements based on carbonation of calcium silicates (CCSC) | Solidia Cement, Calera |
| Demonstration phase | Low-carbonate clinkers with pre-hydrated calcium silicates | Celitement |
| | BYF clinkers (subset of CSA clinkers) | Aether |
| Commercialized | Cements with reduced clinker content (high-blend cements) | LC3, CEMX, L3K, Ecocem |
| | Geopolymers and alkali-activated binders | banahCEM, Zeobond cement |
| | Belite-rich Portland clinkers (BPC) | |
| | Belitic clinkers containing ye'elimite (CSA) | |

**Table 1** from *"Making Concrete Change / Innovation in Low-carbon Cement and Concrete"* Chatham House Report, June, 2018 p. 33

Table 1 gives a good overview of these SCMs and ACs as of summer, 2018; at various speeds and in various places they are all moving to market. Of primary interest to Bay Area builders, of course, are the ones available today and without prohibitive cost or procurement hassle, namely fly ash (of limited value as described above), and *slag* (short for ground, granulated blast furnace slag, a by-product of steel production). Both already have a long track record in concrete around the Bay Area, and slag especially is in good supply. Most of the slag here comes from China via barge, having a transport carbon footprint that is well offset by its value as a cement replacement.

It bears mentioning that a high-volume replacement of Portland cement with fly ash, slag, and most other SCMs generally results in concrete with equal or better quality, but that takes longer to set and to reach its design strength. Since the vast bulk of concrete placed in the world doesn't need to attain its design strength in any particular hurry, that issue can be easily addressed by modifying longstanding code requirements that concrete be judged by it strength *at 28 days*. "Don't be moonstruck", as one wag put it; that is, just by giving concrete more time to mature we can greatly reduce its cement content and thus carbon footprint.

It also bears mentioning that not all cements have the same carbon footprint (see Table 2). There is a large range of both efficiencies and of plant fuels, such as coal, natural gas, or municipal waste, and many "blended cements" which combine lower carbon materials like ground limestone with the pure *clinker* that comes out of the kiln. However, there is as yet no clear rating system by which the embodied carbon of a supply of any particular cement can be readily known. Correcting that deficiency will be a huge and necessary step towards a true low-carbon concrete industry, but for the present a building code must probably treat all cements as the same..

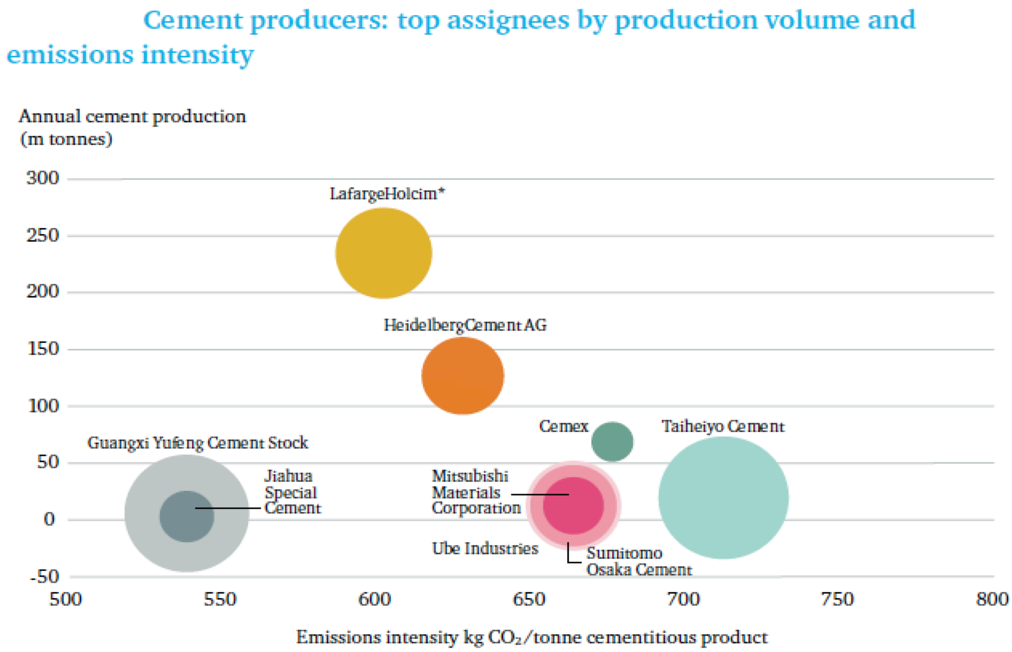
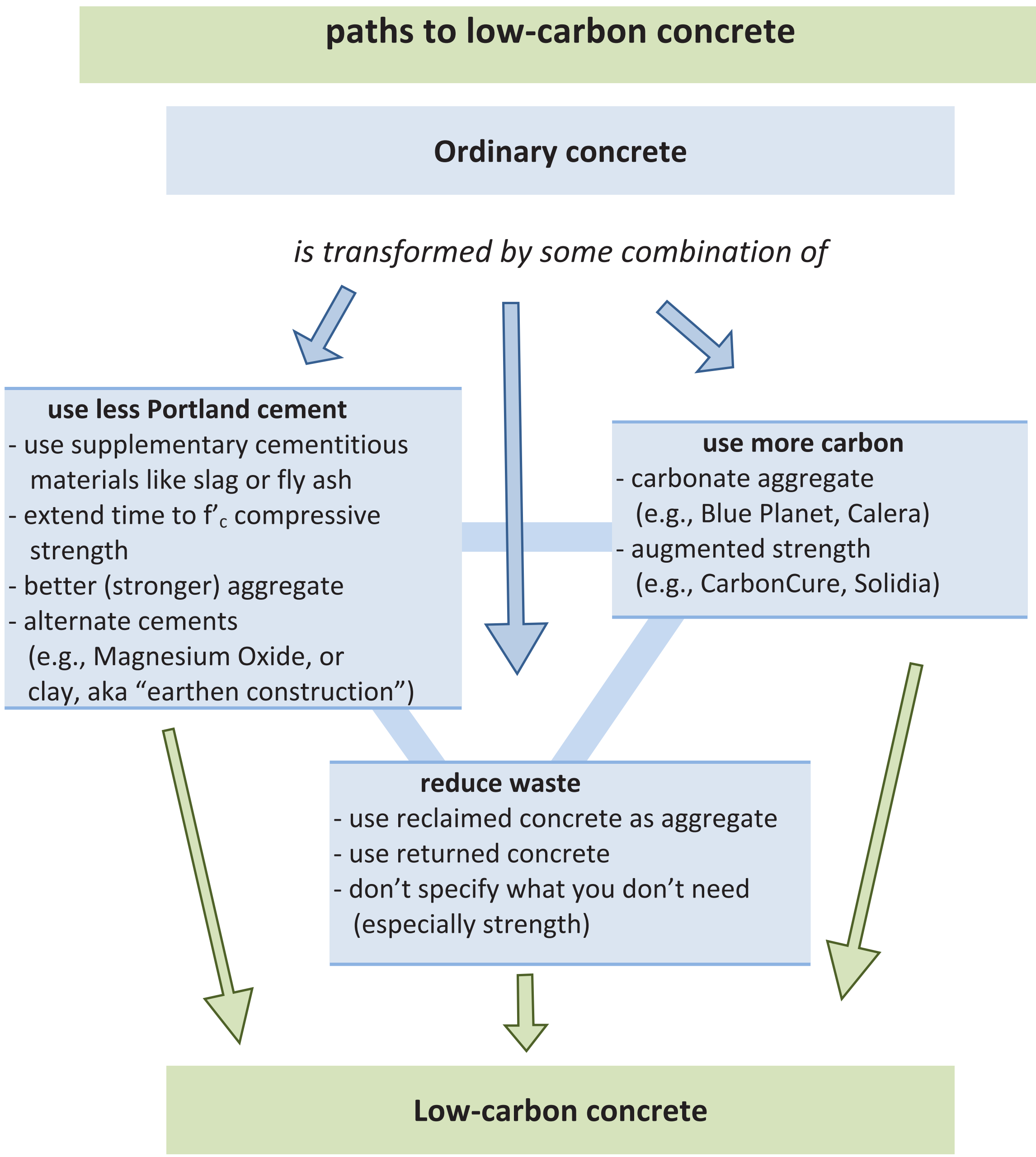



**Table 2** from *"Making Concrete Change / Innovation in Low-carbon Cement and Concrete"* Chatham House Report, June, 2018 p. 30

Decarbonising concrete can and eventually must involve more than changing the cements we use to bind aggregate; it also involves reinventing the aggregate itself. Believe it or not, we need to rethink gravel. And we're on it.

Two prominent examples are 1) Carbon 8 in the UK, gathering particulate emissions from municipal waste burning and turning them into carbon-rich pebbles, and 2) Blue Planet in Los Gatos (near San Francisco), collecting $CO_2$ emissions from the smokestacks of power and cement plants and turning them into carbon-rich limestone. These unglamorous ventures and their ilk hold enormous promise for developing carbon sequestering concrete, but also offer more. In India and other places around the world where concrete construction is booming, the natural supply of sand and gravel is overtaxed, leading to desperate conditions and "sand mafias" that will hurt or kill people to gain access to aggregate deposits. For sand! In those places, technologies like the above stand to solve social problems in addition to GHG emissions.

Even further, $CO_2$ injection technologies such as CarbonCure in Canada show promise as means of storing $CO_2$ in concrete even while increasing its strength.


paths to low-carbon concrete
Ordinary concrete
is transformed by some combination of
use less Portland cement
- use supplementary cementitious materials like slag or fly ash
- extend time to f'c compressive strength
- better (stronger) aggregate
- alternate cements (e.g., Magnesium Oxide, or clay, aka "earthen construction")
use more carbon
- carbonate aggregate (e.g., Blue Planet, Calera)
- augmented strength (e.g., CarbonCure, Solidia)
reduce waste
- use reclaimed concrete as aggregate
- use returned concrete
- don't specify what you don't need (especially strength)
Low-carbon concrete

## 4. Action Plan

There will be three products of this project:

1) Building code amendment

Crafted language consistent with IBC[1] formatting that will require low-carbon concrete, using some combination of *restrictions* (e.g., on cement content), *releases* (e.g., on time required for strength gain, or minimum cement content), and *performance criteria* (e.g., allowing user to meet carbon targets by any combination of modifications of cement, aggregate and placement system, design for re-use, etc.). A first draft is planned for October 2018, and final language must be complete and ready for presentation to the Board of Supervisors by November, 2019.

2) Model specifications

*Commercial* Extensive specifications for larger or more complex projects that may have many different mix designs and strength requirements.

*Residential* Simplified version of the above.

3) Case studies *(at least one of each)*

Commercial, residential, municipal, institutional, and infrastructure

Drafts will be circulated and discussed online and, in some cases, in physical meetings. The grant also assigns some funding for outreach and dissemination.

## 5. Final thoughts

This paper lays out context and action plan to begin to reduce the embodied carbon emissions of buildings and infrastructure by crafting a building code revision. We start with an obvious and relatively simple first target, concrete, but intend that eventually policy here and everywhere will address not just the entire built environment, but all of human industry. In this we join the broader effort to tailor regulation to a circular rather than linear economy, working with and not against the life of the planet.

There are now just enough viable, low-carbon alternatives available to concrete suppliers that this project can be viable in the marketplace. Enterprises like Climate Earth and Skanska are bringing online known concrete mix designs already rated as low-, medium- or high-carbon footprint, greatly simplifying compliance for small and medium producers—and the building officials charged with enforcement. In the slightly longer view, a great number of low-carbon technologies are "waiting in the wings"—ready for usage, but not yet penetrating an extremely protective and risk-averse industry.

You might say that what we intend is to make a legal separation; concrete needs a divorce from, or at least more open relationship with, Portland cement. As codes and standards developed over the past century, that relationship has been enshrined in countless ways. Though some positive accommodations to SCMs have been made, deeply entrenched industry habits still stand in the way of both housing the population soon to come, and protecting us all from the effects of a disrupted climate.

[1] International Building Code, the template for most North American local building codes

European nations have been leading the charge for addressing embodied carbon, but as yet there are few actual, enforced limits to the footprint of concrete in any jurisdiction. Lifting regulatory barriers will help emerging technologies, as will raising barriers to outdated, carbon-intensive ones.

Construction is slow to evolve and change, and in modern times is certainly but a trudging tortoise compared to fast-changing hares like communications, entertainment, and journalism. That is both unsurprising and appropriate; how many of you read this from a floor above grade, and don't want to even *think* about whether or not the building you sit in is safe? Nonetheless, we expect that far more profound changes to the way we build, and what we build with, are inevitable. Concrete construction, it's no great stretch to imagine, will some day abandon the large, loud, smelly trucks that now haul liquid rock, under strict time stress, across cities and highways for delivery to a jobsite. Instead, it will profoundly localize by (in one of many scenarios) using the soil or pulverized concrete at hand, involving no more than a backhoe and a barrel of enzymatic fluid tailored to the site soil to develop whatever strength, texture, durability and elasticity as may be required by the building project.

That is, we can learn to grow buildings.

We hold that enticing image in mind, even as we turn now to the more pedestrian but urgent task of reducing the carbon emissions generated by today's concrete industry. If you can help, we'd love to hear from you.

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[1] *"Embodied Carbon of Buildings and Infrastructure—International Policy Review"* commissioned by Forestry Innovation Investment Ltd (FII). Ryan Zizzo, Joanna Kyriazis, and Helen Goodland, September 2017

[2] "*Circular Economy in the Built Environment: Opportunities for Local Government Leadership"* StopWaste and Arup, June 2018

[3] *"Making Concrete Change / Innovation in Low-carbon Cement and Concrete"* Johanna Lehne and Felix Preston, Chatham House Report, June, 2018

[4] "*Minimum Cementitious Materials Content in Specifications"* ACI 329.1T-18 TechNote American Concrete Institute 2018